

Echoes of the fifth dimension?

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In this article we examine the question of whether the highest energy cosmic ray primaries could be ultra relativistic magnetic monopoles. The analysis is performed within the framework of large compact dimensions and TeV scale quantum gravity. Our study indicates that while this hypothesis must be regarded as highly speculative it cannot be ruled out with present data.

PACS numbers: 98.70.Sa, 13.85.Tp, 11.10.Kk

This past year has seen a massive resurgence of interest in higher dimensional spacetimes [1], a key new concept being the localization of matter, and even gravity on branes embedded in extra dimensions [2]. Depending on the dimensionality and the particular form of this space, the long standing (Planck) hierarchy problem can find alternative solutions. In the canonical example of [3], the Planck scale of the four dimensional world is related to that of a higher dimensional space-time simply by a volume factor,

$$r = \left(\frac{M_{\text{pl}}}{M_*} \right)^{2/n} \frac{1}{M_*}, \quad (1)$$

where $M_* \sim 1$ TeV is the fundamental scale of gravity, $M_{\text{pl}} = 10^{18}$ GeV, and n is the number of extra dimensions. With this factorizable geometry the case of one extra dimension is clearly excluded since gravity would then be modified at the scale of our solar system. However, for $n \geq 2$, r is sufficiently small (the fundamental Planck scale is lowered all the way to the TeV scale) and the model is not excluded by short distance gravitational measurements. A more compelling scenario requires curvature to spill into the extra dimension [4]. Within this framework the background metric is not flat along the extra coordinate, rather it is a slice of anti de Sitter space, due to a negative bulk cosmological constant balanced by the tension of two branes. In this non-factorizable geometry, the curved nature of the spacetime causes the physical scale on the two branes to be different, and exponentially suppressed in the negative tension brane. Such exponential suppression can then naturally explain why the physical scales observed are so much smaller than the Planck scale. Variants of this solution have been discussed by many authors [5]. These models make dramatic predictions which can be directly confronted by current and future collider experiments [6], as well as cosmological observations [7]. The search for extra-dimension footprints in collider data has already started. However, as yet no observational evidence has been found [8].

Another seemingly different, but perhaps closely related subject is the apparent lack of a high energy cut-off in the cosmic ray (CR) spectrum. Over the last few years, several giant air showers have been detected [9], with no sign of the expected Greisen-Zatsepin-Kuz'min (GZK) cutoff [10]. Initiated by single high energy particles hitting the atmosphere, these are large pancake-

shaped slabs of high energy particles which hit the ground at nearly the speed of light and can cover areas of many square kilometers. The origin and nature of the progenitors is, at present, a deep mystery [12]. Protons with energies above the GZK cutoff lose energy rapidly via inelastic collisions with the cosmic microwave background (CMB) and thus presumably must come from a nearby source. This seems unlikely [12]. A typical nucleus of the cosmic radiation is subject to photodisintegration from blue-shifted microwave photons, losing about 3-4 nucleons per traveled Mpc [13]. Gamma rays of the appropriate energy have a short mean free path for creating electron-positron pairs [14]. Although neutrinos can propagate through the CMB essentially uninhibited, at these energies the atmosphere is still transparent, and most of them interact in the Earth if at all. The difficulties encountered in identifying a known particle as candidate have motivated suggestions in favor of “exotic” massive neutral hadrons, whose range is not limited by interactions with the CMB [15]. However, the latter predicts a correlation between primary arrival directions and the high redshift sources, which is not supported by the data set now available [16]. On a different track, it was recently put forward that extra dimensions may in principle hold the key to overcome this puzzle [17]. In this article we shall explore this fascinating possibility.

It has long been known that any early universe phase transition occurring after inflation (say with symmetry breaking temperature T_c), which leaves unbroken a $U(1)$ symmetry group, may produce magnetic monopoles [18]. For instance, minimal $SU(5)$ breaking may lead to “baryonic monopoles” of mass $M \sim T_c/\alpha$, with magnetic charge $U(1)_{\text{EM}}$ and chromomagnetic (or color-magnetic charge) $SU(3)_C$ [19]. Here α stands for the fine structure constant at scale T_c . These monopoles easily pick up energy from the magnetic fields permeating the universe and can traverse unscathed through the primeval radiation. Thus, they are likely to generate extensive air showers [20].* Before proceeding further, it is important to point out that if the monopoles are formed at the usual

*The idea of monopoles as constituents of primary cosmic radiation is actually quite old, it can be traced back at least as far as 1960 [21].

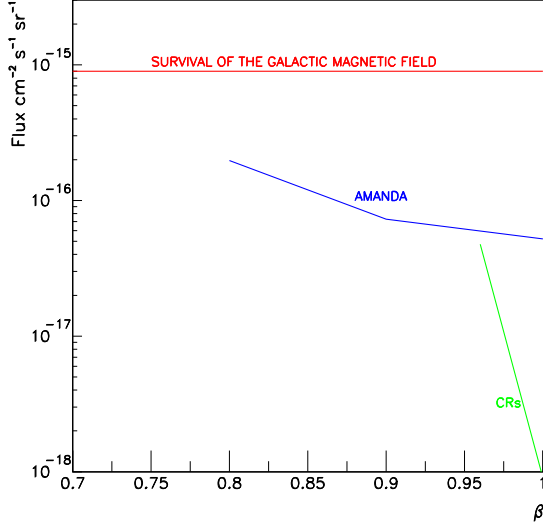


FIG. 1. The upper flux limit of monopoles (as a function of the relativistic parameter β) as observed by the AMANDA experiment, is shown together with the Parker bound and the CR flux assuming that the primaries at the end of the spectrum ($E \geq 5 \times 10^{19}$ eV) have masses $\sim 10^{10}$ GeV.

grand unification (GUT) scale $\sim 10^{15}$ GeV, the energy density overcloses the universe. Thus, to avoid this effect the symmetry breaking scale associated with the production of monopoles has to be shifted to lower energies. Remarkably, if the GUT scale is at $\sim 10^9$ GeV, one would end up with an abundance of relativistic monopoles well below the closure limit, and yet potentially measurable to explain the tail of the CR-spectrum. In addition, for such a critical temperature the observed flux of ultra high energy CRs is below the flux allowed by the Parker limit [22]. Moreover, the CR flux does not violate the upper bound for the monopole flux based on preliminary results quoted by the AMANDA Collaboration (see Fig. 1) [23]. Unfortunately, contrary to the observed CR arrival directions, the expected flux of relativistic monopoles is highly anisotropic, pointing towards the magnetic lines near the Earth [24].

In the multidimensional models, the low-scale unification enables the production of light-mass monopoles, say $M \sim 100$ TeV. Furthermore, the physical embodiment of these theories allows a natural generalization of the 't Hooft-Polyakov monopole providing a convenient set of representations for D1-branes ending on D3-branes, and consequently even lighter monopoles. Note, however, that direct searches at accelerators pretty much exclude masses below a few hundreds of GeV, whereas bounds stemming from quantum effects on current observables turn out to be ~ 1 TeV [25]. The light-mass monopoles could lose and gain energy as they random-walk towards the Earth. The maximum energy attainable before hit-

ting the atmosphere is roughly 10^{25} eV [26]. Therefore, these “particles” would be ultra-relativistic, and the expected flux has no imprint of correlation with the local magnetic field.

To mimic a shower initiated by a proton the monopole must transfer nearly all of its energy to the atmospheric cascade in a very small distance. The large inertia of a massive monopole makes this impossible if the cross-section is typically strong, ~ 100 mb. Wick, Kephart, Weiler and Biermann (WKWB) [26] have recently pointed out that this problem can be avoided in models in which the baryonic monopole consists of q -monopoles confined by strings of chromomagnetic flux. To describe the interactions of such a monopole in air, WKWB have developed a model based on the four following axioms: i) before hitting the atmosphere the monopole-nucleus cross section is roughly hadronic $\sigma_0 \sim \Lambda_{\text{QCD}}^{-2}$ (unstretched state), attaining a geometric growth after the impact; ii) in each interaction an $\mathcal{O}(1)$ fraction of the exchanged energy goes into stretching the chromomagnetic strings of the monopole; iii) the chromomagnetic strings (of tension $T \sim \Lambda_{\text{QCD}}^{-1}$) can only be broken to create monopole-antimonopole pairs (a process highly suppressed and consequently ignored); iv) the average fraction of energy transferred to the shower in each interaction is soft $\Delta E/E \equiv \eta \approx \Lambda_{\text{QCD}}/M$.

Generally speaking, in this set up the monopole will penetrate deeply into the atmosphere (the cross section is comparable to that of a high energy proton). However, since the geometrical cross-section grows proportionally with the Lorentz factor γ , the interaction length (after the impact) shrinks to a small fraction of the depth of the first interaction. Stated mathematically, the unstretched monopole’s string length, $L \sim \Lambda^{-1}$, increases by $\delta L = \Delta E/T$. Recalling that nearly all of the exchanged energy goes into stretching the color magnetic strings, the fractional increase in the length is $\delta L/L = \gamma$, yielding $\sigma_1 \sim (1 + \gamma)/\Lambda_{\text{QCD}}^2$. Now, the total mean free path after the N -th interaction reads,

$$\lambda_N \sim \frac{1}{\sigma_N n_{\text{nuc}}} \sim \frac{\Lambda_{\text{QCD}}^2}{(1 + \sum_{j=1}^N \gamma_j) n_{\text{nuc}}} \sim \frac{\Lambda_{\text{QCD}}^2}{N \gamma n_{\text{nuc}}}, \quad (2)$$

where we have assumed a constant density of nucleons $n_{\text{nuc}} \approx (4/3) \pi A R_0^3$ and we have used the approximation $\gamma_N \sim (1 - \Lambda_{\text{QCD}}/M)^N \gamma \sim \gamma$. Here A stands for the mass number of an atmospheric nucleus, and $R_0 \approx 1.2 - 1.5$ fm. It should also be stressed that for $N = \eta^{-1}$ the approximation has an error bounded by $\lim_{N \rightarrow \infty} (1 - N^{-1})^N = e^{-1}$. For $\eta^{-1} \gg 1$, the total energy traveled between the first interaction and the η^{-1} -th interaction is then

$$\Delta X \sim \frac{\Lambda_{\text{QCD}}^2}{\gamma n_{\text{nuc}}} \sum_{N=1}^{\eta^{-1}} \frac{1}{N} \sim \frac{\Lambda_{\text{QCD}}^2}{\gamma n_{\text{nuc}}} \ln \eta^{-1}. \quad (3)$$

Note that the mean free path for all secondary interactions is $\mathcal{O}(1/\gamma)$ compared to the first one. All in all, a

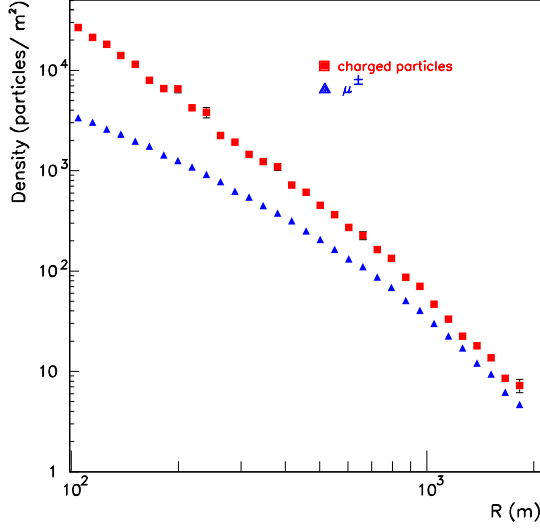


FIG. 2. Lateral distributions of charged particles and muons from AIRES simulations of a 100 EeV monopole with $M = 100$ TeV as a function of the distance to the shower core R . The error bars (obscured by the points themselves in most cases) indicate the RMS fluctuations of the means.

baryonic monopole encountering the atmosphere will diffuse like a proton, producing a composite heavy-particle-like cascade after the first interaction.

To examine the signature of such a cascade, we carried out a Monte Carlo simulation of monopole showers *à la* WKWB using the AIRES program (version 2.2.1) [27]. Specifically, several sets of proton “clumps”, each containing M/Λ_{QCD} , were injected at 100 km a.s.l with the first interaction point fixed according to the proton mean free path. The sample was distributed in the energy range of 1×10^{18} eV up to 3×10^{20} eV, and was equally spread in the interval of 0° to 60° zenith angle at the top of the atmosphere. All shower particles with energies above the following thresholds were tracked: 750 keV for gammas, 900 keV for electrons and positrons, 10 MeV for muons, 60 MeV for mesons and 120 MeV for nucleons. The hadronic interaction was modelled with the SIBYLL package [28]. The results of these simulations were processed with the help of the AIRES analysis programs.

The resulting lateral distributions from a vertically incident monopole of 100 EeV ($\gamma \equiv 10^6$) for muons and charged particles are presented in Fig. 2. A distinctive signature of this kind of shower is the great number of muons among all charged particles. This feature was observed in one not well understood “super-GZK” event [29]. Roughly speaking, a magnetic monopole could then be a candidate primary for the highest energy Yakutsk event. However, WKWB-monopoles associated with a symmetry breaking at $T_c \sim 1$ TeV certainly cannot ex-

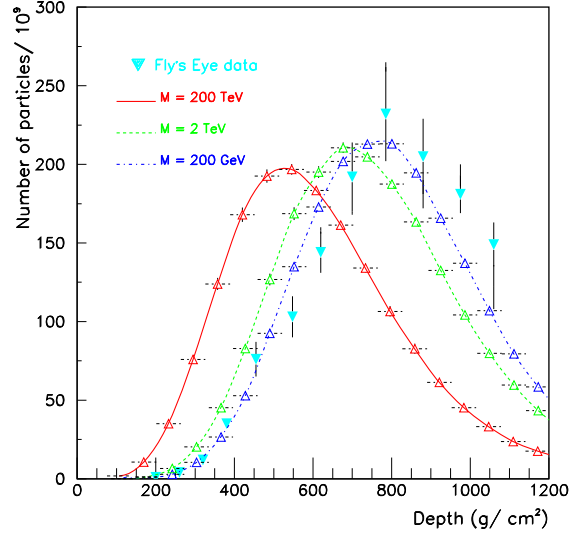


FIG. 3. Atmospheric cascade development of 300 EeV monopole induced showers, superimposed over the Fly’s Eye data. The error bars in the simulated curves indicate the RMS fluctuations of the means.

plain all features of the data at the end of the spectrum. This is illustrated in Figs. 3 and 4. In Fig. 3 we show the longitudinal development of monopole showers superimposed over the experimental data of the world’s highest energy cosmic ray to date [30]. To get some numerical estimates we analyzed the data by means of a χ^2 test [31]. We assume that the set of measured values by Fly’s Eye are uncorrelated (any depth measurement is independent of any other), and make use of the quantity

$$\chi^2 \equiv \sum_{j=1}^q \frac{|x_j - \alpha_j|^2}{\sigma_{x_j}^2}, \quad (4)$$

where q is the total number of points in the analysis, σ_{x_j} is the error on the x_j th coordinate, x_j is the measured value of the coordinate, and α_j the (hypothetical) true value of the coordinate. For masses of a few hundred GeV, the obtained χ^2 increases with rising mass from 13.9 to 58.4. Our analysis indicates that masses above 600 GeV are excluded at more than 99 % C.L. On the other hand, WKWB monopoles of masses around 200 GeV become an alternative explanation for the Fly’s Eye event. It is important to stress that a monopole mass ≈ 200 GeV is not favored by DØ data [32], although one should keep in mind that these bounds are quite model dependent. Moreover, in view of the wide variety of uncertainties in the Fly’s Eye event (the total error in the energy determination is 93 EeV [30]), one may be excused for reserving final judgment until more data is available.

A better understanding of the present situation needs the analysis of the evolution of the shower maximum

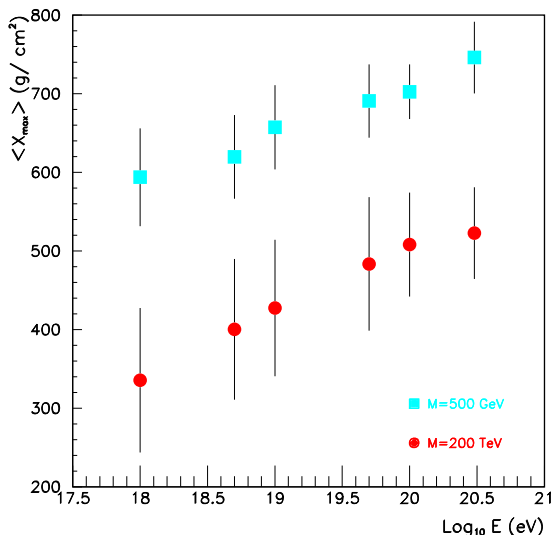


FIG. 4. Average slant depth of maximum of showers initiated by monopoles. The error bars indicate the RMS fluctuations of the means.

X_{\max} with energy. To this end, the charge multiplicity (essentially electrons and positrons) was used to determine the number of particles and the location of X_{\max} by means of four parameter fits to the Gaisser-Hillas function [27]. The situation is summarized by displaying the mean X_{\max} as a function of the logarithm of the primary energy in Fig. 4. It is clear that despite its deep penetration, the monopole cascade develops much faster than a proton shower [33]. It can be seen by inspection that the X_{\max} values produced by ultra-relativistic monopoles ($E \gtrsim 10^{19}$ eV) with masses $\gtrsim 200$ TeV are inconsistent with those reported by the Fly’s Eye experiment, whereas the X_{\max} values of showers induced by lighter monopoles, $M \lesssim 500$ GeV, are within 1 standard deviation of the scarce “super-GZK” data [9].

Whether or not the laws of physics should be formulated in more than four dimensions is still unclear. The possible existence of compact large extra dimensions brings with it low energy phase transitions [34], providing a profitable arena for baryonic light-mass monopole production. If this is the case, the monopoles could be accelerated to ultra-relativistic energies as they roam through space, inducing extensive air showers from time to time after hitting Earth atmosphere. As we have discussed in this article, the atmospheric cascade of monopoles with $M \lesssim 500$ GeV could reproduce quite well the main features of the recorded giant cosmic ray showers. Certainly, more data is needed to test the WKWB hypothesis. Forthcoming ground arrays and satellites, such as the Auger Observatory [35], the next SCROD [36], and EUSO/OWL/AirWatch [37–39], will help to increase the CR sample and more precise limits on the air shower ob-

servables will be available, shedding light on the ideas discussed in this paper.

ACKNOWLEDGMENTS

We would like to thank Haim Goldberg, Carlos Nuñez, and Tom Weiler for useful discussions. We are also indebted to Gia Dvali for insightful comments on the manuscript, and to Peter Nießen, Doug Cowen, and Christian Spiering for pointing us to the unpublished AMANDA results. The work was supported by CON-ICET (Argentina) and the National Science Foundation.

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